Single Beam Polarization Holographic Grating Recording

Nickolai Kukhtarev,* George Dovgalenko, Galen C. Duree, Jr., and Gregory J. Salamo
Physics Department, University of Arkansas, Fayetteville, Arkansas 72701

Edward J. Sharp
U.S. Army Research Laboratory, Fort Belvoir, Virginia 22060

Barry A. Wechsler and Marvin B. Klein
Hughes Research Laboratories, 3011 Malibu Canyon Road, Malibu, California 90265
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Single beam holographic grating recording, based on the photogalvanic coupling between orthogonal birefringent modes, is demonstrated in a photorefractive $BaTiO_3$ crystal.

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In holography, two waves, signal and reference, are needed to record information about the phase and amplitude of the signal wave. This is normally accomplished using one optical beam for the signal wave and a separate beam for the reference wave.

In this paper, we demonstrate both theoretically and experimentally the possibility of hologram recording using only one input beam, which is automatically split into two eigenmodes in a birefringent photogalvanic crystal. The interaction between the two orthogonally polarized eigenmodes, ordinary (o) and extraordinary (e), in the crystal, via a photogalvanic current [1–5], then writes a holographic grating. This grating is subsequently read using the same single recording beam either in real time or at a later time. Consequently, the great advantage of this technique is that there are reduced restrictions on the coherence length and alignment of the incident laser light since the reference and signal beams are formed inside the crystal.

The coupling between orthogonal waves inside the crystal is depicted in Fig. 1. An optical beam is incident onto a crystal at angle θ. The incident field then splits into two crystal eigenfunctions characterized by the ordinary and extraordinary wave vectors $\mathbf{k}_o$ and $\mathbf{k}_e$. In the region of overlap between the two eigenwaves in the crystal, a holographic grating is written. More formally, the electric field of the incident light in the crystal can be written as a superposition of quasiplane waves,

$$\mathbf{E}=\sum_s [\mathbf{C}_s e^{i\eta_s}+\text{c.c.}] , \tag{1}$$

where $\eta_s=\omega t-\mathbf{k}_s\cdot\mathbf{r}$ and "s" is a sum over the ordinary and extraordinary crystal eigenmodes. In this expression, the birefringence of the photorefractive crystal is contained in the wave vector $\mathbf{k}_s$ and ω is the optical frequency of the incident field.

The propagation of the electric field in the crystal is described by Maxwell's wave equation:

$$\nabla\times(\nabla\times\mathbf{E})+\frac{1}{c^2}\frac{\partial^2\mathbf{D}}{\partial^2 t}=0 . \tag{2}$$

To take into account the fact that our coefficients of the expansion in Eq. (1) are time dependent we write the displacement vector as

$$\mathbf{D}=\hat{\varepsilon}\mathbf{E}+\delta\mathbf{D} . \tag{3}$$

Substituting Eqs. (1) and (3) into the wave equation, while making the slowly varying envelope approximation, we get an expression [6] for the wave amplitudes $\mathbf{C}_s$:

$$\begin{aligned}(\mathbf{k}_s\cdot\nabla)\mathbf{C}_s &= -\frac{i\omega^2}{2c^2}\langle\delta\mathbf{D}e^{-i\eta_s}\rangle_{t,r}\\ &= -\frac{i\omega^2}{2c^2}\langle\delta\hat{\varepsilon}\mathbf{E}e^{-i\eta_s}\rangle_{t,r} ,\end{aligned} \tag{4}$$

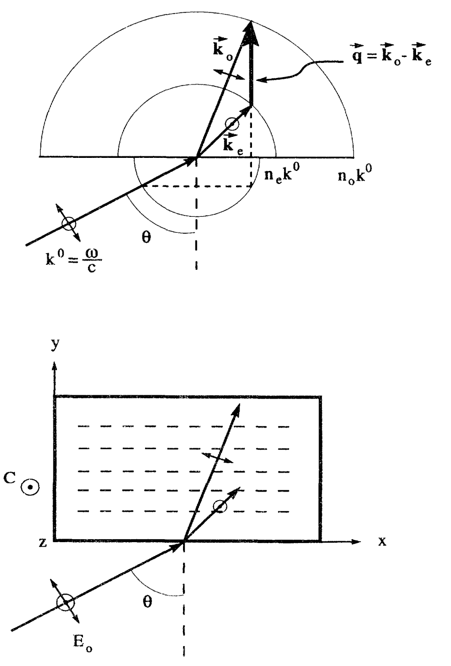

FIG. 1. $BaTiO_3$ in crystallographic system of axes with k-vector diagram.

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where the angular brackets denote standard time and space averages and $\delta\mathbf{D}=\delta\hat{\varepsilon}\mathbf{E}$.

In this paper, we present a calculation which yields values for the wave amplitudes $\mathbf{C}_s$ and we compare these values with experimental measurements in $BaTiO_3$. Agreement between theory and experiment therefore demonstrates and characterizes the existence of *single beam polarization holographic grating recording*. We have also made use of the single beam polarization grating to demonstrate a *single beam interferometer*.

The logic for the calculation for the wave amplitudes $\mathbf{C}_s$ using Eq. (4) is simple. First, we develop an expression for the change in the permittivity tensor $\delta\hat{\varepsilon}$ in terms of the optically generated photorefractive internal space charge field $\mathbf{E}$. Second, we develop a corresponding expression for the internal space charge $\mathbf{E}$ field in terms of known crystal parameters. Third, combining these two expressions, we present an expression for the change in permittivity tensor $\delta\boldsymbol{\varepsilon}$ which when used in the wave equation, Eq. (4), yields two coupled equations for the field amplitudes. These two equations are, therefore, written only in terms of known crystal parameters. Fourth, the two coupled equations are solved for the field amplitudes $\mathbf{C}_s(t)$.

In the first step, the change in the permittivity tensor is governed by the linear electro-optic effect. In particular,

$$\delta\varepsilon_{ij}=-[\hat{\varepsilon}(\hat{\mathbf{r}}\mathbf{E})\hat{\varepsilon}]_{ij}\,, \tag{5}$$

where $\hat{\mathbf{r}}$ is the electro-optic tensor, $\mathbf{E}$ is the photoinduced quasistatic electric field in the crystal, and $\hat{\varepsilon}$ is the permittivity tensor of an unilluminated crystal. In the case of a $BaTiO_3$ crystal with point group symmetry $4mm$, the components of $\delta\hat{\varepsilon}$ are, for the $\mathbf{z}$ axis along the optic axis $\mathbf{c}$, given by

$$\begin{aligned}&\delta\varepsilon_{xx}=\delta\varepsilon_{yy}=-n_o^4r_{13}E_z,\quad \delta\varepsilon_{zz}=-n_e^4r_{33}E_z\,,\\&\delta\varepsilon_{xz}=-(n_on_e)^2r_{51}E_x,\quad \delta\varepsilon_{yz}=-(n_on_e)^2r_{51}E_y\,,\end{aligned} \tag{6}$$

where n_o and n_e are, respectively, the ordinary and extraordinary indices of refraction.

In the second step, in order to find the change in the permittivity tensor $\delta\hat{\varepsilon}$ using Eq. (6), we must calculate the photoinduced electric field. For photorefractive crystals this induced electric field $\mathbf{E}$ can be calculated using the equation of continuity and the Poisson equation for the charge ρ and electric current $\mathbf{j}$. These equations can be written as

$$\frac{\partial\rho}{\partial t}=-\nabla\cdot\mathbf{j},\quad \nabla\cdot\hat{\varepsilon}\mathbf{E}=4\pi\rho\,. \tag{7}$$

To write a holographic grating using a single beam as shown in Fig. 1, the only possibility for coupling of the orthogonal extraordinary and ordinary modes is through the photogalvanic current

$$j_n^{\mathrm{ph}}=\beta_{nkl}^*E_kE_l^*+i\beta_{nl}[\mathbf{E}\cdot\mathbf{E}^*]_l\,, \tag{8}$$

where the first term represents the symmetric part of the current while the second term is the antisymmetric part. Using

$$\mathbf{E}=\mathbf{e}_\perp C_\perp e^{-i\mathbf{k}_e\cdot\mathbf{r}}+\mathbf{e}_\parallel C_\parallel e^{-i\mathbf{k}_o\cdot\mathbf{r}}+\text{c.c.}\,, \tag{9}$$

and

$$\mathbf{e}_\parallel=\mathbf{e}_x\cos\theta-\mathbf{e}_y\sin\theta,\quad \mathbf{e}_\perp=\mathbf{e}_z\,. \tag{10}$$

In Eq. (8), the j_y component along the grating wave vector $\mathbf{q}\equiv\mathbf{k}_o-\mathbf{k}_e$ shown in Fig. 1, with spatial modulation is given by

$$j_y^{\mathrm{ph}}=(\beta_s+i\beta_a)\sin\theta(C_\perp C_\parallel^*e^{iqy}+\text{c.c.})\,. \tag{11}$$

Here $\beta=\beta_s+i\beta_a$, β_s is the symmetric part, β_a the antisymmetric part of the photogalvanic tensor, and $C_\parallel$ and $C_\perp$ are the components of the ordinary and extraordinary waves. In these expressions the sum "s" over the eigenmodes has been specifically written as ordinary "$\parallel$" and extraordinary "$\perp$." From Eq. (7), we can write for the photoinduced electric field $\mathbf{E}$

$$\frac{\partial\mathbf{E}}{\partial t}=-\frac{4\pi}{\varepsilon}(\mathbf{j}^{\mathrm{ph}}+\sigma\mathbf{E})\,, \tag{12}$$

where a drift current, proportional to the crystal conductivity $\boldsymbol{\sigma}$, has been added. The y component of the solution of (12) can be written as

$$E_y(t)=E_y(0)e^{-t/\tau}-\frac{4\pi}{\varepsilon}\int_0^t j_y^{\mathrm{ph}}e^{(t'-t)/\tau}dt'\,, \tag{13}$$

where $E_y(0)$ is the electric field for $t\le 0$ and $\tau=\varepsilon/4\pi\sigma$ is the relaxation time. Taking into account the fact that $E_y(0)=0$, and using Eq. (11), we can write an expression for the space charge field in terms of known crystal variables:

$$E_y(t)=-\frac{\beta\sin\theta}{\sigma}(1-e^{-t/\tau})[C_\perp C_\parallel^*e^{i\mathbf{q}\cdot\mathbf{y}}+\text{c.c.}]\,. \tag{14}$$

In the third step we can combine the expressions for $\delta\boldsymbol{\varepsilon}$ and $\mathbf{E}$ and write the wave equation, Eq. (4), for the field amplitudes as

$$\begin{aligned}\frac{dC_\perp}{dy}&=-i\beta_\perp|C_\parallel|^2C_\perp-\frac{\alpha_\perp}{\cos\theta_\perp}C_\perp\,,\\\frac{dC_\parallel}{dy}&=i\beta_\parallel^*|C_\perp|^2C_\parallel-\frac{\alpha_\parallel}{\cos\theta_\parallel}C_\parallel\,,\end{aligned} \tag{15}$$

where $\theta_\parallel,\theta_\perp$ are the angles inside the crystal, $\alpha_\perp$ and $\alpha_\parallel$ are absorption coefficients for extraordinary and ordinary polarized light waves and

$$\begin{aligned}\beta_\perp&\equiv\frac{\pi r_{51}}{\lambda_0\sigma}n_o^2n_e\sin^2\theta\beta(1-e^{-t/\tau})\,,\\\beta_\parallel&\equiv\frac{n_e}{n_o}\beta_\perp\,.\end{aligned} \tag{16}$$

In the expressions for $\beta_\perp$ and $\beta_\parallel$ we have kept only the larger r_{51} terms. Note that the equations for the field amplitudes are given only in terms of known crystal parameters.

In the fourth step, for the special case of weak energy exchange between the two coupled orthogonal waves, i.e., $|\beta_\perp||C_\parallel|^2|y| < 1$, we can write the solution of Eq. (15) as

$$C_\perp(y) = C_\perp^0 f_\perp + i\beta_\perp I_\parallel^0 C_\perp^0 (1-f_\parallel)\cos\theta_\parallel/\alpha_\parallel ,$$
$$C_\parallel(y) = C_\parallel^0 f_\parallel + i\beta_\parallel I_\perp^0 C_\parallel^0 (1-f_\perp)\cos\theta_\perp/\alpha_\perp , \qquad (17)$$

where $f_{\perp,\parallel} \equiv \exp(-\alpha_{\perp,\parallel} y/\cos\theta_{\perp,\parallel})$ and $C_{\parallel,\perp}^0$ are input values, $I_{\parallel,\perp}^0 \equiv |C_{\parallel,\perp}^0|^2$.

Using Eq. (15) we can then write the solution for the intensities

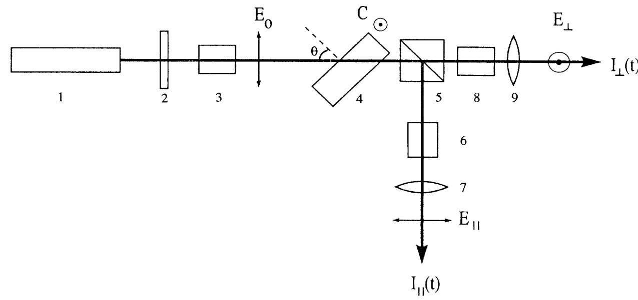

FIG. 2. Experimental apparatus. (1) Ne-Ne laser (632.8 nm); (2) λ/4 wave plate; (3,6,8) polarizers; (5) beam splitter; (7,9) lenses.

$$I_\perp(y) = I_\perp^0 f_\perp^2 + I_\parallel^0 I_\perp^0 (1-f_\parallel) f_\perp i(\beta_\perp - \beta_\perp^*)\cos\theta_\parallel/\alpha_\parallel , \quad I_\parallel(y) = I_\parallel^0 f_\parallel^2 + I_\parallel^0 I_\perp^0 (1-f_\perp) f_\parallel i(\beta_\parallel^* - \beta_\parallel)\cos\theta_\perp/\alpha_\perp , \qquad (18)$$

which can then be used to write the energy exchanged form $I_\perp(z)$ as

$$\Delta I_\perp = I_\perp(y) - I_\perp^0 f_\perp^2 = I_\parallel^0 I_\perp^0 \frac{2\pi r_{51}}{\lambda_0 \alpha_\parallel \sigma} n_o^2 n_e \sin^2\theta \beta_a (1-e^{-t/\tau})[1-\exp(-\alpha_\parallel y/\cos\theta_\parallel)]\exp(-\alpha_\perp y/\cos\theta_\perp)\cos\theta_\parallel . \qquad (19)$$

This is an expression for the energy exchange between the two *orthogonal eigenmodes* caused by the photogalvanic tensor β_a and the corresponding holographic grating. In particular, for the initial state of recording, i.e., $t/\tau \ll 1$, we can write the energy exchange as

$$\Delta I_\perp = I_\parallel^0 [I_\perp^0 \exp(-\alpha_\perp y/\cos\theta_\perp)] \frac{8\pi^2}{\lambda_0 \varepsilon \alpha_\parallel} r_{51} n_o^2 n_e \times \sin^2\theta \beta_a [1-\exp(-\alpha_\parallel y/\cos\theta_\parallel)] t \cos\theta_\parallel , \qquad (20)$$

where $I_{\parallel,\perp}^0$ are the input intensities after Fresnel losses, i.e., $I_\perp^0 = T_e I_{0\perp}$, $I_\parallel^0 = T_o I_{0\parallel}$, and T_e and T_o are the crystal transmission coefficients. When this expression is applied to our specific $BaTiO_3$ crystal we use the parameters $\alpha_\perp = 2.74$ cm^{-1}, $\alpha_\parallel = 0.67$ cm^{-1}, $y_0 = 0.3$ cm, $\lambda_0 = 6.328\times 10^{-5}$ cm, $I_{0\perp} = 0.24$ mW, $I_{0\parallel} = 1.4$ mW, $n_o = 2.41$, $n_e = 2.36$, $T_\perp = 0.44$, $T_\parallel = 0.725$, $\theta = 60°$, $r_{51} = 800$, and $\beta_a = 4\times 10^{-9}$ A/W as reported for the same crystal in Ref. [4]. Using these parameters the predicted value of energy exchange is about 10%.

The experimental apparatus used to measure the coupling between the orthogonal eigenmodes is shown in Fig. 2. A laser beam from a 5 mW HeNe laser passed through a variable polarization rotator before it was incident on a cobalt doped $BaTiO_3$ photorefractive crystal. The laser was oscillating at 632.8 nm and the beam incident on the crystal had a beam diameter of 1.5 mm. The incident beam was linearly polarized and entered the crystal with most of the light polarized as an *o* eigenmode (1.4 mW) while a small component was polarized as an *e* eigenmode (0.24 mW). As a result, energy was exchanged between the *o* wave and the *e* wave. In particular, the amplitude and time dependence of the *e* wave was monitored using a photodiode and chart recorder. Using a polarizer at the exit of the crystal the *e* wave was isolated onto the photodiode. The chart recorder signal therefore represented the evolution of the amplitude of the *e* wave generated by two-wave mixing. The amplitude was measured and determined to increase by 10% over a response time on the order of 100 min with an incident angle of 60°. The solid curve in Fig. 3 shows the energy exchange dependence on the incident angle θ as predicted in Eq. (20). The curve indicates that a maximum energy transfer occurs for an angle of about 60°. The value of 60° is due in part to the angular dependence of the transmission coefficients. The data points indicate good agreement between theory and the observed value of $\Delta I_\perp$. Each data point in Fig. 3 represents the average of four data runs at that particular angle. Experimentally, the grating observed has all the properties associated with a photorefractive holographic grating. For example, if the

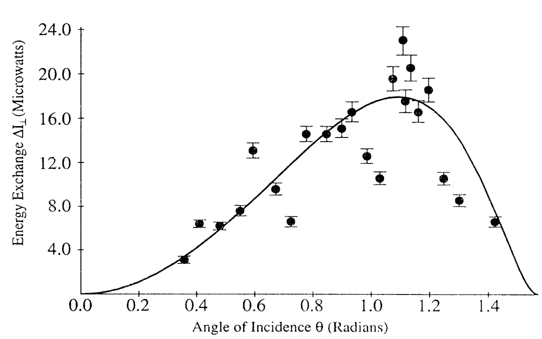

FIG. 3. Plot of the energy exchange versus the angle of incidence θ. $\delta I_\perp \sim f(\theta) = T_{o\perp} T_{\parallel e} \sin^2\theta$ and $T_{o\perp}, T_{\parallel e}$ are the transmission coefficients for the ordinary and extraordinary waves.

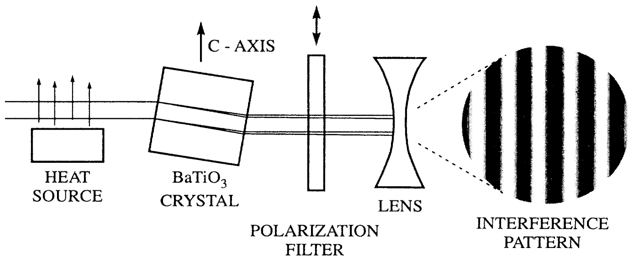

FIG. 4. Single beam interferometer.

incident beam is blocked, the grating persists for days and can be immediately read at any time. Also, the grating was easily erased using uniform illumination. Finally, the speed at which the grating was written decreased with increasing intensity and the magnitude of the grating was independent of incident intensity.

In addition to demonstrating single beam polarization holographic grating recording, we also demonstrated its application. In particular, we demonstrated that the single beam polarization holographic grating could be used to detect motion or optical path changes introduced in a single-arm interferometer. That is, as shown in Fig. 4, when a heat source was brought near the interferometer arm the slight change in path caused the incident beam to strike a slightly different area on the crystal. As a result, a new grating started to form. Meanwhile, the old grating begins to get erased. During this transient time, however, both gratings, old and new, exist simultaneously. Since the displacement between the two gratings is small, both are "read" simultaneously. Consequently, two signal beams are produced at the same time and result in interference fringes. The fringe spacing associated with the observed fringe pattern is then a measure of the relative displacement of the incident beam, or angular separation between the old and new signal beams. A similar result was observed using a plate in the interferometer arm. When the plate was rotated slightly fringes appeared and then gradually disappeared as the new grating became dominant. The significance of this demonstration is that it makes clear the possibility of the development of single beam holography using the polarization grating.

In summary, we report the first observation of single-beam holographic grating recording using orthogonal eigenwaves in a photogalvanic-photorefractive crystal. The observed grating strength was significant as indicated by 10% energy exchange between one eigenmode and the other. We have also demonstrated the operation of a single beam interferometer using the polarization grating. These observations make plausible a demonstration of writing an image in the crystal by imprinting an image onto one eigenmode before it enters the crystal. We are presently carrying out experiments to demonstrate such applications.

*Present address: Physics Department, Alabama A&M University, Normal, AL 35762.

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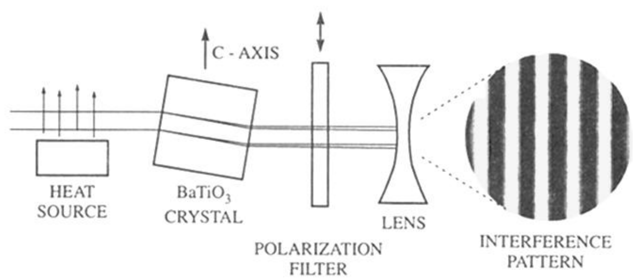

FIG. 4. Single beam interferometer.